

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### HYDROACOUSTIC BLOCKAGE CALIBRATION FOR DISCRIMINATION: RESULTS FROM 2003 INDIAN OCEAN CRUISE, AND IMPLoding SPHERE CALIBRATION SOURCE DEVELOPMENT

Philip E. Harben<sup>1</sup>, Eric Matzel<sup>1</sup>, Donna K. Blackman<sup>2</sup>, and Doug Clarke<sup>1</sup>

Lawrence Livermore National Laboratory<sup>1</sup>, University of California at San Diego<sup>2</sup>

Sponsored by National Nuclear Security Administration  
Office of Nonproliferation Research and Engineering  
Office of Defense Nuclear Nonproliferation

Contract No. W-7405-ENG-48<sup>1</sup>, DE-FC03-01SF22356<sup>2</sup>

#### **ABSTRACT**

The central focus of research in FY04 was to develop a tool to assess hydroacoustic blockage that could easily be used by analysts to predict which hydroacoustic monitoring stations can be used in discrimination analysis for any particular event. The research involves two approaches (1) model-based assessment of blockage, and (2) ground-truth data-based assessment of blockage. The goal is to reliably determine all hydroacoustic stations that can support a discrimination analysis from any event location in the world's oceans. An important aspect of this capability is to eventually include reflected T-phases where they reliably occur. This year a prototype analyst tool was developed using model-based blockage assessment with provision for future inclusion of databased assessment. The tool presents the analyst with a map of the world, and plots raypath blockages from stations to sources. The analyst inputs source locations and blockage criteria, and the tool returns a list of blockage status from all source locations to all hydroacoustic stations. The model-based blockage tool assessment reliability is currently limited by the coarse bathymetry of existing databases. In collaboration with BBN Inc., the Hydroacoustic Coverage Assessment Model (HydroCAM) that generates the blockage grid files that serve as input to the prototype analyst tool, is being extended to include high-resolution bathymetry databases in key areas that increase model-based blockage assessment reliability.

The 2003 Indian Ocean (IO) cruise sources were analyzed at all IO stations for frequency content, signal-to-noise, and blockage. The 2003 and 2001 cruises together provide a 17-event database of ground-truth explosive sources that are widely distributed within the IO basin. This will be added to the earthquake event database to provide the basis for extension of the analyst tool to databased blockage assessment. The 2003 cruise also provided the data to compare sphere and signals underwater sound (SUS) small explosive sources. The SUS source provides larger amplitude signals at long range. Both sources provide energy above background noise in the 20 – 100 Hz bandwidth.

The sphere source was modeled using a hydrodynamic code. Peak pressures increased as the sphere internal air pressure decreased, and the bubble pulse period and amplitude decreased with decreasing internal pressure. Relatively small variations in the internal pressure from one sphere to the next accounts for the observed variation in the bubble pulse period. By including a shell of fluid with the density and mass of the glass sphere in the model, some complex waveform features observed in the field tests were reproduced in the models. The model differs notably from test results in the shock-wave pulse width and the bubble pulse period, possibly because glass crushing effects could not be included in the model. Poor repeatability in the clustered 5-sphere source design gave rise to a line-sphere system that should result in an azimuth independent waveform, enhanced survivability, and modularity.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### **OBJECTIVE**

The objective of this research is to enhance discrimination capabilities for events located in the world's oceans. Two research and development efforts are needed to achieve the stated objective: 1) improvement in discrimination algorithms and their joint statistical application to events, and 2) development of an automated and accurate blockage prediction capability that will identify all stations and phases (direct and reflected) from a given event that will have adequate signal to be used in a discrimination analysis. More emphasis will be put on the first R&D need in the future. This paper will focus on the progress made on the second R&D need.

The strategy for improving blockage prediction in the world's oceans is to improve model-based prediction of blockage and to develop a ground-truth database of reference events to assess blockage. This two-pronged approach emulates the approach taken in seismic monitoring. As much as possible, seismic tools and know-how will be utilized in hydroacoustic blockage assessment. Improving model-based blockage prediction entails, first and foremost, improving resolution of the bathymetry databases used in blockage calculations. The BBN Inc. developed code HydroCAM is the basis for all model-based grid file calculations. Improving HydroCAM's blockage modeling capability starts with improving the bathymetry databases the blockage calculations are based on. Research has focused on developing the capability in HydroCAM to utilize variable resolution bathymetry data and hence incorporate high-resolution "spotlight" bathymetry databases into the overall bathymetry data utilized in blockage calculations.

Research has also focused on the development of a blockage assessment software tool. The software tool is envisioned to develop into a sophisticated and unifying package that optimally and automatically assesses both model-based and databased blockage predictions in all ocean basins, for all NDC stations, and accounting for reflected phases (Pulli *et al.*, 2000). A prototype blockage assessment tool has been developed. The model-based software tool effort focuses on the Diego Garcia station in the Indian Ocean and uses a suite of blockage grids produced by HydroCAM to assess blockage.

The ground-truth element of blockage assessment began with the assembly and delivery of an earthquake event database recorded at Diego Garcia and Cape Leeuwin stations in the Indian Ocean and implementation of an automated event-loading schema. A database rich in high-frequency ground-truth events is important; consequently the database is being augmented with explosive events whenever possible. The Indian Ocean cruises in 2001 and 2003 have supplied 17 high-frequency ground-truth events that are widely distributed over the Indian Ocean basin. Further development of the sphere source, particularly an improved multi-sphere source, offers a relatively inexpensive way to assess high-frequency blockage through ground-truth experiments on ships of opportunity. Future plans call for integration of the database element with the blockage assessment software tool and the eventual addition of reflected phases in the analysis. In the immediate future, based on analyst input, the tool will be improved to provide ease-of-use and integrated with waveform databases.

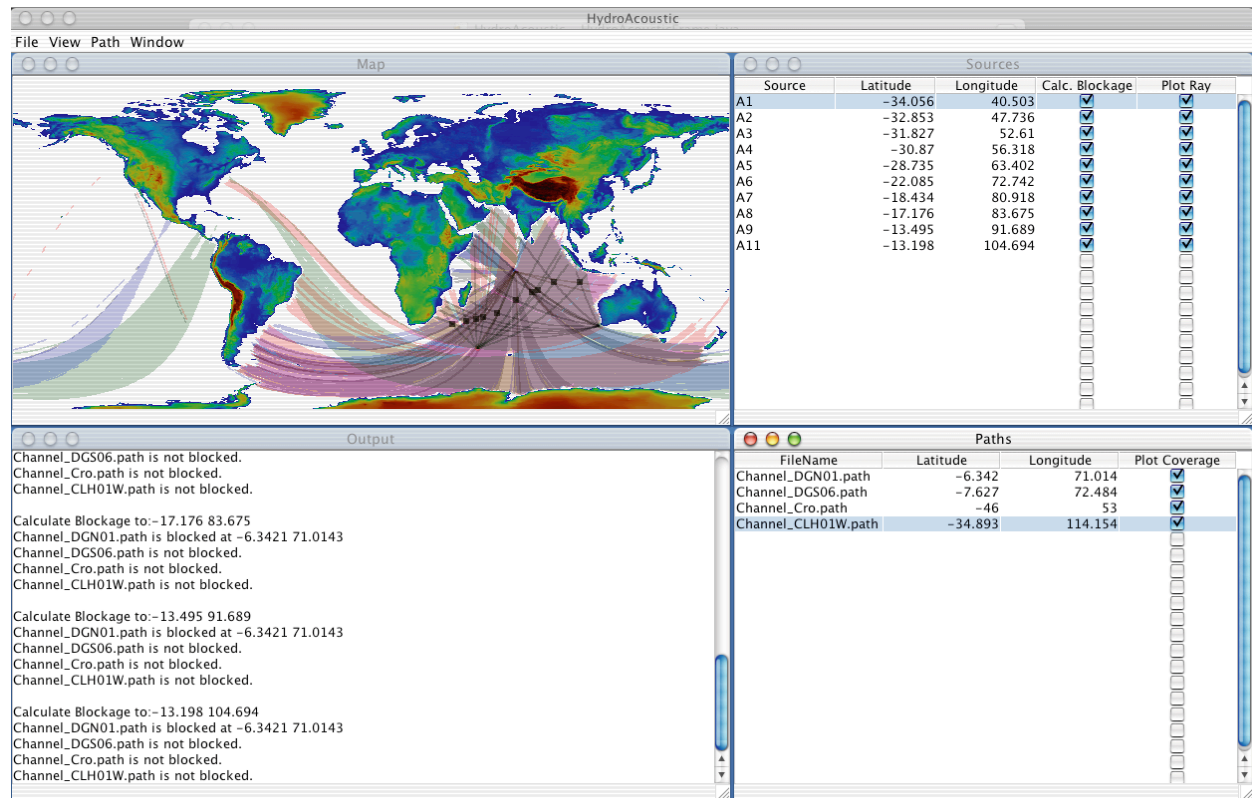
### **RESEARCH ACCOMPLISHED**

The primary research and development accomplished in FY04 was the development of a prototype analyst tool that employs a model-based approach to assess blockage from event(s) to all hydroacoustic monitoring stations. Analysis of the Indian Ocean cruises and source recordings was accomplished as well as advanced modeling and system design of the imploding sphere source.

The model-based research and development has focused on utilizing the modeling capability of HydroCAM to develop a basic software tool that can be used to access a suite of blockage grid files (based on different blockage criteria) calculated by HydroCAM. The critical shortcoming in current HydroCAM blockage modeling is due to present-day worldwide bathymetry databases. The nominal wavelengths in the hydroacoustic monitoring band are about 15 m to 1.5 km, whereas the current average resolution of the ocean surface slope and topography with satellite altimetry is 24 km (Smith and Sandwell, 1997). The vast majority of the world's ocean basin area is deeper than the sound channel depth, and consequently, poor bathymetry resolution is not a factor in blockage prediction. Instead, accurate blockage prediction hinges on augmenting the worldwide database with high resolution (nominally 200 m from ship soundings) bathymetry in "spotlight regions," particularly near monitoring stations. Collaboration

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

with BBN Inc. to develop and enhance HydroCAM modeling and supporting bathymetry databases is tightly coupled to improvements in the model-based analyst tool accuracy.



**Figure 1. The user interface to the blockage assessment tool plots station coverage and unblocked paths to specific sources in the upper left panel. The user defines source locations in the top right panel, and stations in the lower right panel, and is provided a list of path blockage assessment to each source in the bottom left panel.**

The user interface to the blockage assessment tool is shown in Figure 1. The tool is divided into four panels, the top left panel providing a scalable map of all input sources and monitoring stations with optional plotting of station coverage. In the example below, all eleven of the 2003 Indian Ocean cruise source locations are plotted, as are the three Indian Ocean station coverage (Diego Garcia, Cape Leeuwin, and Crozet Is.) maps and unblocked paths from stations to sources (black lines). The panel below the map shows an assessment of blockage to each station from a given source in list format. The rightmost panels are editable lists of source locations (top) and station/path locations (bottom). The tool provides an analysis for specific user-specified blockage criteria given in depth cutoff criteria. A 1,000 m cutoff criteria, for example, means that a specific source-receiver path is considered blocked if bathymetry above 1,000 m is encountered anywhere along the path. Grid files produced by HydroCAM were based on a number of cutoff criteria from 1,000 m to sea level. The user cutoff criteria specify the grid file the analyst tool uses. In general, more blocked paths are predicted with deeper cutoff criteria.

Features of the prototype model-based blockage assessment tool include:

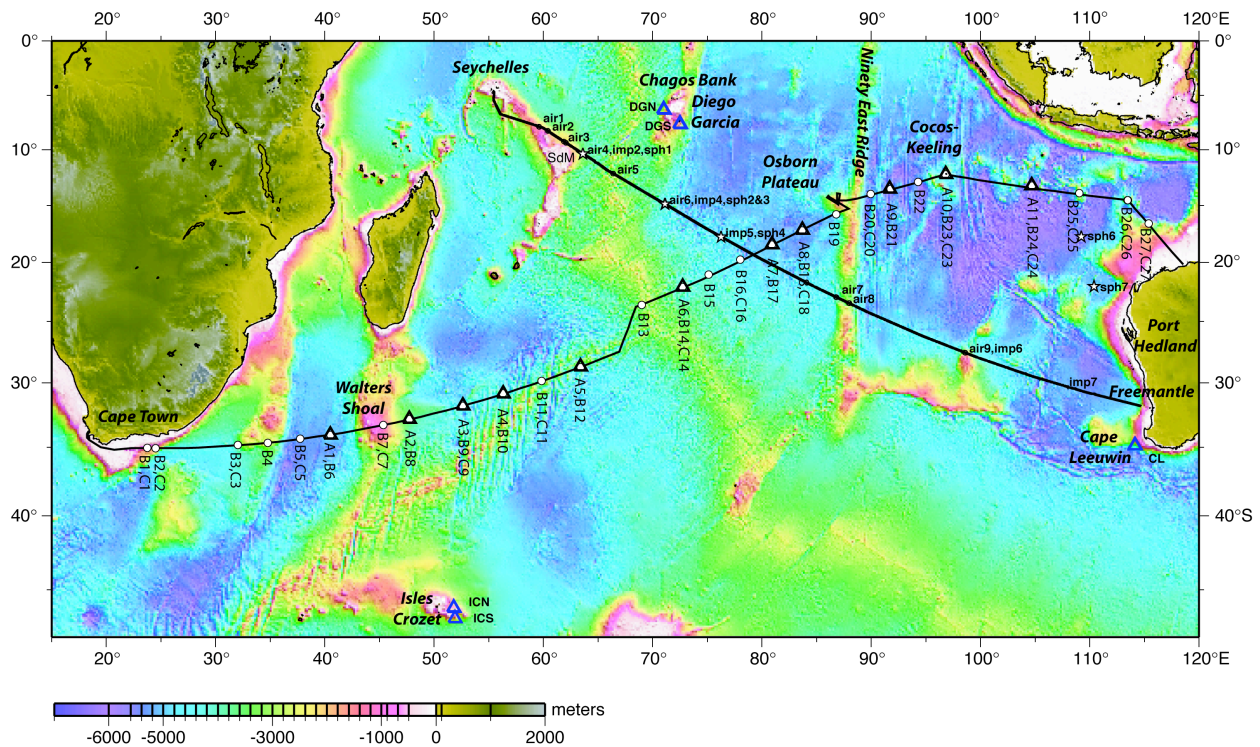
- Platform independent JAVA tool.
- Does not require other software (such as MATLAB or HydroCAM) to run.
- Does not require specialized graphics tools or capability.
- Reads HydroCAM "path" files and plots the coverage defined by the outer contour.
- Coverage for multiple "paths" and stop criteria can be read in, plotted and manipulated simultaneously.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

- User defined “source” locations can be input manually or read in as a list and edited directly within the tool.
- Blockage identifications can be made simultaneously for multiple source-receiver pairs.
- Multiple blockage criteria can be tested simultaneously.
- Path coverage and source-receiver raypath plots can be toggled on and off for individual elements.
- Blockage identification can be toggled on and off for individual sources.
- The Map figure can be scaled up and down to allow focus on particular areas of the globe.

Future development of the blockage assessment tool will focus on implementing a parallel ground-truth data-driven assessment capability based on a database of ground-truth event. Although many explosive or other high-frequency events that are identified will be included in the database, most of the database content will consist of earthquake events. The tool will also be linked to waveform databases so that on unblocked paths the tool can deliver the event waveforms recorded during a time window containing the predicted arrival time.

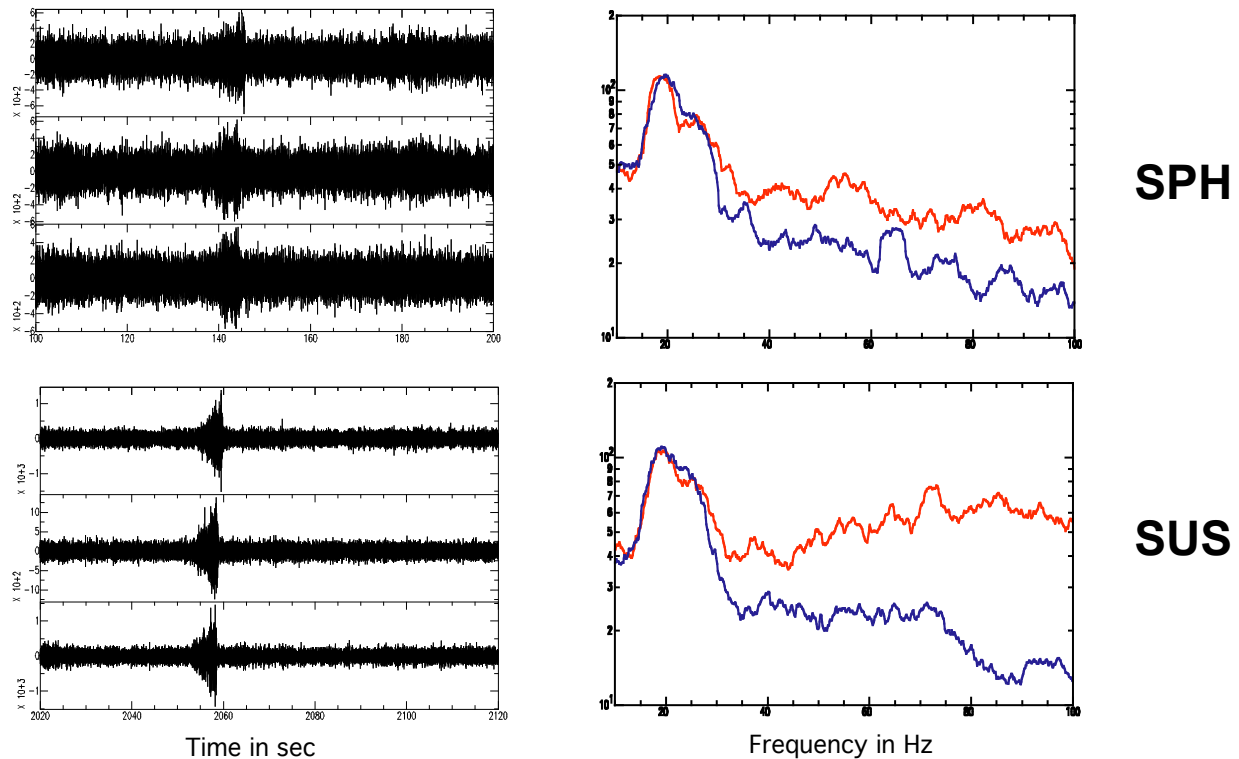
The second Indian Ocean cruise took place in 2003, sailing from Cape Town, South Africa, to Port Hedland, Australia. The ship tracks of both the 2001 and 2003 cruises are shown in Figure 2. The cruises resulted in 17 high-frequency ground-truth events within the Indian Ocean basin that will become part of the databased blockage assessment database. Imploding spheres, an airgun array, SUS charges and an electro-acoustic source (HX-554 by University of Washington's Applied Physics Lab) were investigated as possible calibration sources. The airguns required shallow depths for firing; consequently, energy entered the sound channel primarily by scattering off the sea floor. Detailed, and currently unavailable, bathymetry data are required to accurately model near-source scattering at frequencies above 20 Hz. The HX-554 is now operational and provides a well-calibrated signal, however use of this system is significantly more challenging, logistically, than the other sources.



**Figure 2. The Indian Ocean basin map shows the ship track of the 2001 cruise (Seychelles –Freemantle) and the 2003 cruise (Cape Town – Port Hedland) and the locations of all SUS, sphere, and airgun sources.**

The SUS charges and 5-sphere impllosion systems were both fired at several station locations so that a comparison of long-range propagation characteristics could be made. Such a comparison is shown in Figure 3. The recordings are at Cape Leeuwin from station A7, a range of 3,752 km. The top left waveform (high passed at 40 Hz) shows the

arrival from the sphere source, and the bottom left waveform (high passed at 40 Hz) shows the SUS arrival at each hydrophone of the triad. Clearly, the SUS source has better signal-to-noise at long range than has the sphere source. Although the two sources have about the same peak pressure at 1 m from the source, the longer signal duration and relatively lower frequency content of the SUS source makes for superior long-range propagation at the depths of these tests (nominally 700 m). The spectra on the right plot signal amplitude (red) and pre-event background noise (blue) for the sphere source (top) and the SUS source (bottom). Both source types have no appreciable energy below about 20 Hz but do span the monitoring band between 20 Hz and 100 Hz.

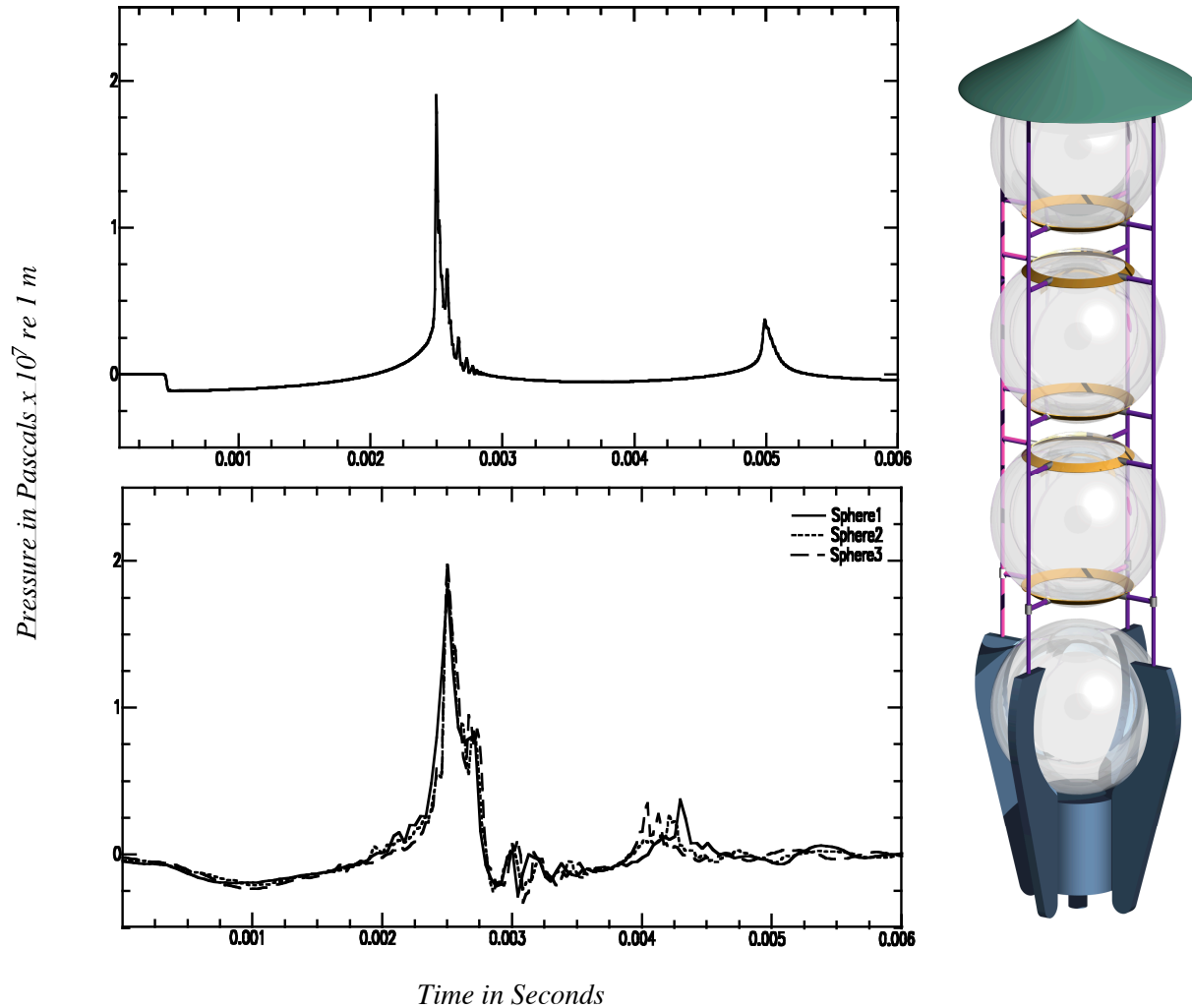


**Figure 3.** The sphere source waveform (top left) and spectra (top right) are compared to the SUS source waveform (bottom left) and spectra (bottom right) as recorded at Cape Leeuwin, 3,752 km from the source. Note that the spectra plots event amplitude (red/upper) and pre-event background noise amplitude (blue/lower).

The sphere source (Harben *et al.*, 2000) signal was modeled using the hydrodynamic code CALE (C-code, Arbitrary Lagrangian, Eulerian) to predict overpressures at 1 m from the source (R. T. Barton, 1985; J. Hagelberg, 2003). Several models were run varying only the internal pressure of the sphere. Peak pressures increased as the sphere internal air pressure decreased, and the bubble pulse period and amplitude decreased with decreasing internal pressure. When the internal pressure was a sixth of standard atmospheric pressure, the peak pressure matched field tests. We found that the temperatures reached in blowing and sealing the glass spheres would result in internal pressures very close to one-sixth standard atmospheric pressure. In addition, relatively small variations in the internal pressure from one sphere to another accounts for the observed variation in the bubble pulse period. Figure 4 shows the modeled signal waveform of the source (top plot). The model included a shell of fluid with the density and mass of the glass sphere. Including a glass like fluid in the model gave rise to the trailing shock peak and high-frequency hash, and it resulted in a sharper or pointed bubble pulse. The field tests shown in the bottom plot have those same features; consequently, we can conclude that the density contrast of the glass compared to seawater plays

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

wave pulse width and the bubble pulse period. Both differences may be the result of the crushing of the solid glass that must be occurring, but that is not captured in the simplified model.



**Figure 4. The modeled sphere implosion source signal (top plot) compared to three field tests at 680 m depth (bottom plot). An artist's conception of a linear and modular multi-sphere system is shown on the right.**

Although the single sphere-source is highly repeatable, the clustered 5-sphere source showed poor repeatability. This is because the 5-sphere source is not cylindrically symmetric; consequently, source waveform features show a dependence on azimuth. The 5-sphere system also was lacking in ruggedness and exhibited damage after repeated firings on the 2003 cruise. An improved design is shown on the right of Figure 4. The in-line system should result in an azimuth independent waveform and be rugged. An added feature of the design is that any number of spheres can be utilized as source needs dictate.



## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### CONCLUSIONS AND RECOMMENDATIONS

A prototype model-based blockage assessment tool has been developed and is undergoing analyst evaluation. The tool makes use of blockage grid files produced by HydroCAM; consequently, improvement in model-based blockage assessment reliability of the tool is tightly coupled to improvement in HydroCAM, particularly in the resolution of the bathymetry databases used by HydroCAM to create the blockage grid files. The blockage assessment tool had been developed with provision for including a ground-truth databased assessment component. This will be added in the near future and, depending on the density of ground-truth data, should increase reliability of overall blockage assessment in spotlight regions. In addition, future blockage assessment tool development will focus on interfacing to waveform databases, and will thereby automatically provide the analyst with the raw waveforms from all unblocked stations.

The 2001 and 2003 Indian Ocean cruises have shown that 1.8 lb SUS charges and 5-sphere implosion sources can be used for ocean basin calibration of travel time and blockage provided the sources are at SOund Fixing and Ranging (SOFAR) channel depths. In all, the cruises have contributed 17 widely distributed Indian Ocean events to the ground-truth database. Since these sources are small and are recorded at relatively low signal-to-noise, there is little hope that they could be useful in understanding reflected T-phases at high frequency (above 30 Hz). A larger explosion (30 – 300 lbs) in the SOFAR at a strategic location from a known reflecting coastline would be needed to determine the signal-to-noise reduction from reflection as a function of frequency.

The imploding sphere source was studied via field tests as well as by hydrodynamic modeling. The field tests have shown highly repeatable signal waveforms from single spheres but poor repeatability from the 5-sphere design. The 5-sphere design also proved mechanically vulnerable after repeated uses. A new linear multi-sphere design promises to produce a repeatable, multi-sphere source waveform and high survivability as well as to offer flexibility in the number of spheres employed. Hydrodynamic modeling has provided insight on the source waveform. The role of internal pressure and the glass density contrast explains many specific waveform features and variations. Modeling has not correctly predicted the pulse width of the implosion. This may be because the phenomenon of glass fracturing and the resulting crushing during implosion was not accounted for in the models.

### REFERENCES

- Barton, R. T. (1985), "The CALE Computer Code," *Numerical Astrophysics*. Boston, Jones and Bartlett.
- Hagelberg, J., (2003), CALE Implementation Guide, Lawrence Livermore National Laboratory, Livermore, California, UCRL-ID-155540, September 2003.
- Harben, P. E., C. . Boro, L. . Dorman, and J. . Pulli (2000), Use of Imploding Spheres: An Alternative to Explosives as Acoustic Sources at Mid-Latitude SOFAR Channel Depths, UCRL-ID-139032.
- Pulli, J. J., Z. . Upton, R. . Gibson, J. . Angell, T. . Farrell, and R. . Nadel (2000), Characterization of Reflected Arrivals and Implications for Hydroacoustic Test-Ban-Treaty Monitoring, BBN Tech. . Memor. . W1380.
- Smith, W. H. F. . and D.T. . Sandwell (1997), Global Seafloor Topography from Satellite Altimetry and Ship Soundings, *Science*, 277, 1956-1962.